Published in Seismological Review Letters, **76**, 551–553, issue of Sept/Oct 2005.

Obituary

Keiiti Aki (1930 – 2005)

Seismologist and leader

Everyone called him Kei, the intellectual leader who for forty years brought new methods to a more quantitative understanding of dynamic processes within the Earth. Kei Aki died on May 17 this year on Réunion Island, the "hot spot" in the Indian Ocean that had been his home since retirement from academic life in the United States. He will be known for his many research results in seismology as well as for his team leadership in developing probabilistic estimates of seismic hazard.

Kei was born in Japan to a family of engineers with a 100-year tradition of education and openness to the west, but then, as he wrote: "When I was 19 years old, I applied to the Department of Geophysics of the University of Tokyo, partly because of the simplest entrance examination, only on three subjects, English, Mathematics and Physics." He continued there to a Ph. D. thesis on spectra of stationary stochastic seismic waves and briefly held a fellowship at the California Institute of Technology in the early 1960s — where he greatly impressed Charles Richter and Frank Press before returning to the University of Tokyo in 1963. When Press left Caltech to head Earth Sciences at the Massachusetts Institute of Technology, he recruited Kei to the MIT faculty in 1966 and thus to an American academic career.

His scientific achievements include some of the earliest studies interpreting the radiation pattern of seismic surface waves to estimate fault orientation and direction of slip at the earthquake source. In 1966 he showed how to estimate the seismic moment of an earthquake from seismograms. This measure, equal to the product of rigidity, fault area ruptured, and average fault slip, became recognized as the best way to characterize the size of an earthquake source and the strength of its long-period waves. Seismic moment is now routinely estimated from seismic body waves, regional waves, surface waves, and Earth's normal modes. Among its many uses are integrative estimates of the earthquake-associated motion between two tectonic plates. When compared with total plate motion derived from geomagnetic, geological, and geodetic methods, one learns the fraction of motion on a particular plate boundary that takes place suddenly in earthquakes — permitting estimates of the long-term seismic hazard. Seismic moment has recently been used to look for changes in stress-loading, using earthquakes that almost exactly repeat themselves.

The SI units of seismic moment are Newton-meters, and proposals have been made to name 10^{3N} such units (for some integer N) as a new unit of seismic moment, the Aki. Kei himself commented on such proposals with amusement, while noting the merits of conversion to a logarithmic scale (the moment magnitude), which is dimensionless. But a linear scale is clearly needed and ideas will perhaps soon crystallize with a specific suggestion, so that the great range of seismic moments measurable from waveforms lies between a nano-Aki and a tera-Aki.

In the 1960s Kei pioneered scaling laws of seismic spectra, concluding that typically the spectra of radiated seismic displacements, after correction for propagation effects, have a corner frequency below which the spectrum is approximately flat and proportional to seismic moment, and above which it decays like $(\text{frequency})^{-2}$. He began a series of studies showing that seismic coda (the waves following an identifiable first-arriving signal) can be used to provide stable measurements of source spectra; and that coda can change in ways that may enable measurement of *in situ* stress changes prior to an earthquake.

In the 1970s, working with Lee, Husebye and Christoffersson, he interpreted seismic wave arrival times at a network of stations to determine the three-dimensional inhomogeneities of Earth structure beneath the network. His inverse method is a scientific basis of PASSCAL (the Program for Array Seismic Studies of the Continental Lithosphere), a cornerstone of the globally operating IRIS Consortium, and has been applied via instrument deployments on every continent to quantify the vertical and lateral structure of the crust and upper mantle. Working with Andrews, Madariaga, Das and Papageorgiou he developed quantitative studies of fault models that examined the physical features controlling earthquake nucleation, spontaneous rupture, and the eventual stopping of the rupture process on a fault surface because of some barrier or asperity — or because the rupture has run out of a region of stress concentration. Such studies of the physics of earthquake faulting provide the scientific basis for understanding and predicting damaging ground motions.

As an observational science, seismology deals with vast ranges of scale. From smallest to largest, wavelengths range over more than 10^8; the time windows over which data are analyzed range over more than 10^9; ground displacements range over more than 10^{11} from the smallest signals at quiet sites (about 0.1 nanometer) up to the tens of meters of fault displacement in great earthquakes; and, as Kei showed, the size of seismic sources ranges over about 10^{25} from microfractures in laboratory rock samples up to megafractures causing the greatest earthquakes such as that of December 26, 2004, offshore Sumatra. Consequently seismology in practice is a loose amalgamation of diverse specialities, and few seismologists have good knowledge of more than a small fraction of the total subject. Some seismologists interpret signals to map out the remaining commercial deposits in a producing oil field; others quantify strong ground shaking and measure how it decays with distance from earthquakes in tectonically active areas, or from the more rare but very destructive earthquakes that can occur within stable continents. It is usually different seismologists who study the Earth's internal structure, from the great depths of the inner core, up through the mantle, and on up to the shallowest structures in the crust — to identify targets for an archeological dig, or find a buried pipeline. Seismology is used to measure rates of continental deformation, to monitor compliance with nuclear test ban treaties, and for a host of applications in seismic hazard assessment and related issues in urban planning, emergency management, and insurance. Kei and his students worked in many of these applied specialities, and he himself retained a strong interest and level of optimism that practical successes will eventually be achieved in what he regarded as the most important application of them all, namely earthquake prediction.

In March 1975, he wrote me a letter beginning "I wonder if you would be interested in coauthoring a text book on theoretical seismology with me..." It was a surprise, for even then he was a senior figure. I was so junior, and we were not then personally acquainted. I accepted, and will never forget our first meeting. As background to our conversation, he jotted down some apparently random descriptive phrases in different places on a large sheet of paper that over the course of an hour filled to become the working plan and table of contents for what was published years later as *Quantitative Seismology*, now translated (with its more than 6000 equations) into Russian, Chinese, and Japanese. His goal was a unified presentation of those methods of seismology that are used in data interpretation by different groups of people — who in their separate specialities had developed their own jargon and notation and special practices, and whom he thought would benefit from a survey that brought out underlying ideas.

I have never known anyone who worked so efficiently. But he sustained this style for decades, as best evidenced by his guidance of more than 50 diverse Ph. D. theses, and his writing scientific papers with more than 100 different co-authors from 1955 to 2005.

After 18 years teaching at MIT, Kei moved in 1984 to the University of Southern California, where he could more directly experience earthquake phenomena. He was the founding Science Director of the Southern California Earthquake Center, where input from earthquake geology was used together with the fault model of quantitative seismology to generate output useful for earthquake engineers, city managers, and the media. The concept of seismic moment was central to unifying information from plate tectonics, geology, geodesy, and historical and instrumental seismology. The public transfer of integrated information was made in the form of probabilistic estimates of earthquake hazards. SCEC was one of the first NSF-funded Science and Technology Centers. It continues to flourish.

In his 16 years at USC, as well as meeting his commitments to work through SCEC with earthquake engineers and policymakers dealing with seismic hazard, he continued a vigorous publication record in source theory and propagation theory, and studies of particular earthquakes. He and his students and colleagues found evidence for seismic waves that are guided by fault zones; they explored non-linear site effects associated with ground motion from large nearby earthquakes that cannot be predicted from superposition of the motion from smaller events; and they noted relationships between coda wave attenuation and seismicity.

He was long fascinated with volcano seismology, another field with intellectual and practical challenges for which a quantitative understanding has long been sought. Volcanoes exhibit spontaneous ground motions caused by interactions of fluid, gaseous, and solid media. Kei continued this work in "retirement", especially on Réunion with its local seismographic network. He made quantitative models of volcanic tremor, estimated the location of magma chambers, monitored magma ascent, and searched for the physical causes of what he observed.

Earthquakes and volcanoes represent a wide range of phenomena that for centuries have aroused feelings of mystery and fear, and that today attract our attention for intellectual and economic reasons as we seek to understand the scientific and engineering consequences of shaking ground. Keiiti Aki probed more deeply into these phenomena and with greater insight than any other individual. He advanced our understanding of how earthquakes nucleate, how they reach their eventual size, and how their signals spread throughout the Earth, carrying information on their origin and on the medium they have traversed. He showed us how to tease out this scientific information about sources and Earth structure. And he faced successfully the challenges of taking information about strong ground motions into the earthquake engineering community, and to national and regional policymakers needing guidance on managing earthquake hazard.

His scientific leadership was complemented by his organizational leadership, including terms as President of the Seismological Society of America, President of the Seismology Section of the American Geophysical Union, and as Chair of the U.S. National Research Council's Committee on Seismology. He was a member of the U.S. National Academy of Sciences, a Fellow of the American Academy of Arts and Sciences, and a medallist of the Seismological Society of America. In December 2004 he came halfway round the world from his island home to San Francisco, to the American Geophysical Union's annual meeting of more than 10,000 participants, where he received the William Bowie medal — AGU's highest honor — and enabled many former students and colleagues memorably to celebrate his life's work (see photo). In April 2005 he was awarded the European Geophysical Union's highest honor, the Beno Gutenberg medal.

Kei shared ideas with his students and numerous post-docs. He helped them to shine, and many are now leaders of their field and of their institutions in Europe, Asia, and the Americas. He himself was a gentle leader, informal and approachable, pleased with the many honors that came his way but never needing them, calm in adversity, and always with a smile on hearing an interesting new idea — especially if outrageous but supported by some type of observation. With his pioneering studies of seismic moment, his results on spectral scaling and coda stability, and his demonstration of successful methods to invert data for three-dimensional Earth structure, he provided the quantitative methods that now guide the work of thousands of Earth scientists around the world.

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